Lawrence Livermore National Laboratory

October/November 2011

Science & Technology Review

Proton Therapy Advances Cancer Treatment

Also in this issue:

Light Deflector Garners Award

Award-Winning Debugging Tool

Plutonium Transport Demystified

About the Cover

Thanks to a technology transfer agreement, a proton beam that is highly focused on a tumor and creates only low-dose side effects in surrounding tissue may begin to appear in hospitals in 2014. The revolutionary particle accelerator, designed to provide lifesaving therapy to cancer patients, grew out of a Livermore technology pursued to support the nuclear weapons program. As described in the article beginning on p. 4, a private company in Livermore, California, with assistance from Laboratory scientists, is now refining the device for clinical use.

Cover design: Daniel S. Moore

About *S&TR*

At Lawrence Livermore National Laboratory, we focus on science and technology research to ensure our nation's security. We also apply that expertise to solve other important national problems in energy, bioscience, and the environment. *Science & Technology Review* is published eight times a year to communicate, to a broad audience, the Laboratory's scientific and technological accomplishments in fulfilling its primary missions. The publication's goal is to help readers understand these accomplishments and appreciate their value to the individual citizen, the nation, and the world.

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Please address any correspondence (including name and address changes) to *S&TR*, Mail Stop L-664, Lawrence Livermore National Laboratory, P.O. Box 808, Livermore, California 94551, or telephone (925) 423-3432. Our e-mail address is str-mail@llnl.gov. *S&TR* is available on the Web at str.llnl.gov.

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Moon and Earth May Be Younger Than Thought

Livermore chemist Lars Borg and his collaborators have analyzed three isotopic systems, including the elements lead, samarium, and neodymium, found in ancient lunar rocks. The researchers have determined that the Moon could be younger than originally estimated—just 4.36 billion years old. (Moon image courtesy of National Aeronautics and Space Administration.) The common estimate of the Moon's age is 4.56 billion years old (roughly the same age as our solar system) as determined by mineralogy and chemical analysis of Moon rocks gathered during the Apollo missions.

The research has implications for the age of Earth as well. The common belief is that the Moon formed as a result of a giant impact into Earth and then solidified from an ocean of molten rock (magma). "If our analysis represents the age of the Moon, then Earth must be fairly young as well," says Borg. "This age is in stark contrast to a planet like Mars, which is argued to have formed about 4.53 billion years ago. If the age we report is from one of the first-formed lunar rocks, then the Moon is about 165 million years younger than Mars and about 200 million years younger than large asteroids."

The isotopic measurements were made by taking samples of ferroan anorthosite (FAN), which is considered to represent the oldest type of lunar crustal rock. According to Borg, these analyses showed that either the Moon is likely to have solidified significantly later than most previous estimates or the long-held belief that FANs are flotation cumulates of a primordial magma ocean is incorrect.

Chemical evolution of planetary bodies ranging from asteroids to large rocky planets is thought to begin with differentiation through solidification of magma oceans hundreds of kilometers in depth. Earth's Moon is a typical example of this type of differentiation. However, one interpretation of the collaboration's findings is that this process may not have occurred on the Moon. "The isotopic measurements showed that a specific FAN yields consistent ages from multiple isotopic dating techniques and strongly suggest that the ages record the time at which the rock crystallized," says Borg.

Borg's collaborators included researchers from University of Copenhagen, Université Blaise Pascal, and Carnegie Institution's Department of Terrestrial Magnetism. The team's research appeared in the September 1, 2011, edition of *Nature.*

Contact: Lars Borg (925) 424-5722 (borg5@llnl.gov).

Agreement with China to Develop Clean Energy

The Laboratory has signed an agreement with the Clean Energy Research Institute in China to conduct joint research and development of clean energy technologies. Huaneng Power International, Inc., the largest power company in the world, formed the Clean Energy Research Institute. Under the memorandum of understanding, the Laboratory will create a stronger relationship with Huaneng and both parties will conduct research analysis and data exchange as established under the U.S.–China Clean Energy Research Center (CERC) that was created last year.

The two parties will exchange information and technology on carbon capture and sequestration (CCS), enhanced oil recovery, shale gas, and power engineering. Specifically, Livermore brings expertise in CCS, advanced materials science, engineering and design, and energy systems analysis. "We plan to work on applied scientific challenges in large-scale projects and deployments," says Julio Friedmann, Livermore's director of the carbon management program. "We look forward to working closely with our Chinese counterparts to find opportunities for collaboration that serve the needs of both nations,"

The Laboratory has a strong relationship with the Chinese through CERC, a project that facilitates joint research and development of clean energy technologies, including CCS. CCS is a process that separates and captures carbon dioxide from industrial and power plant flue streams, then compresses the gas and stores it underground in deep geologic formations. The process prevents greenhouse gas emissions from entering the atmosphere where they can contribute to global warming and climate change.

Contact: Tomás Díaz de la Rubia (925) 422-6714 (diazdelarubia1@llnl.gov).

Commentary by Thomas F. Gioconda

Innovations and Partnerships to Meet National Needs

IT'S exciting to work at Lawrence Livermore because here we can help "create the country's future" through advances in science and technology to meet important national needs. Our successes can be attributed to a focus on mission, innovative technical breakthroughs to address mission needs, and the formation of partnerships with experts in industry and at other institutions to get the job done.

The continuous, dynamic interactions among mission, innovation, and partnership are vividly illustrated in this issue of *S&TR*. Beginning on p. 4, the feature article describes an innovative idea for a technology that was born out of our program to sustain the nation's nuclear weapons stockpile. That idea has since found an important potential application in health care and is now being developed in partnership with private industry.

In 2014, hospitals around the country may begin to have much greater access to a highly effective tool for fighting cancer: proton therapy. Radiation therapy using x rays is a common method of cancer treatment, but it often damages healthy tissue around the tumor. Radiation therapy using a beam of protons can be better focused on the targeted tumor and creates only low-dose side effects in surrounding tissue. However, current proton therapy requires a very large and costly machine. For these reasons, only 31 proton treatment centers exist in the world, with just nine in the U.S.

More than a decade ago, Livermore researchers began exploring a novel approach for designing an extremely compact accelerator to be used for radiography, which is a key tool for stewardship of the nation's nuclear weapons stockpile. A physicist at the Laboratory, who was working with the University of California (UC) Davis Cancer Center, became aware of the work and recognized the potential for the technology, called the dielectric wall accelerator (DWA), to revolutionize proton radiography for cancer treatment. In 2004, we began a Laboratory Directed Research and Development project to explore DWA's feasibility, with the enthusiastic support of the Cancer Center. The demonstration was successful, making the technology attractive for investors.

In 2007, TomoTherapy, Inc., a company already active in the development and sale of traditional radiation treatment systems, entered into a technology transfer agreement to continue work on the new accelerator. No other company was close to making a device with the small size, low cost, and treatment effectiveness of DWA. TomoTherapy has since participated in setting up a new venture called Compact Particle Acceleration Corporation (CPAC), located in Livermore just blocks from the Laboratory. As the article describes, CPAC is making remarkable progress developing DWA. CPAC general manager Anthony Zografos notes, "A number of Laboratory staff are in and out almost constantly assisting us."

As a cancer survivor myself, I appreciate this lifesaving work in the advanced treatment of cancer. It is good to be working with colleagues who are helping to provide a solution that is effective and accessible.

Mission, innovation, and partnerships also figure strongly in this issue's research highlights. Our two R&D 100 Award winners this year—the so-called "Oscars of invention"—are described, as is a collaborative project to investigate some of the baffling properties of plutonium.

As an example, one of the R&D 100 Award winners, STAT (for Stack Trace Analysis Tool), was developed from the emerging urgent need for the capability to efficiently debug computer programs that run on computers with hundreds of thousands and up to millions of processors. This unique tool was the product of a partnership with researchers from the University of Wisconsin at Madison and University of New Mexico. STAT is particularly important for Livermore because supercomputer simulations are essential to progress in virtually every mission area of the Laboratory. The tool has been used elsewhere to test its effectiveness on a wide range of supercomputer platforms. Further development and commercialization of STAT are next steps.

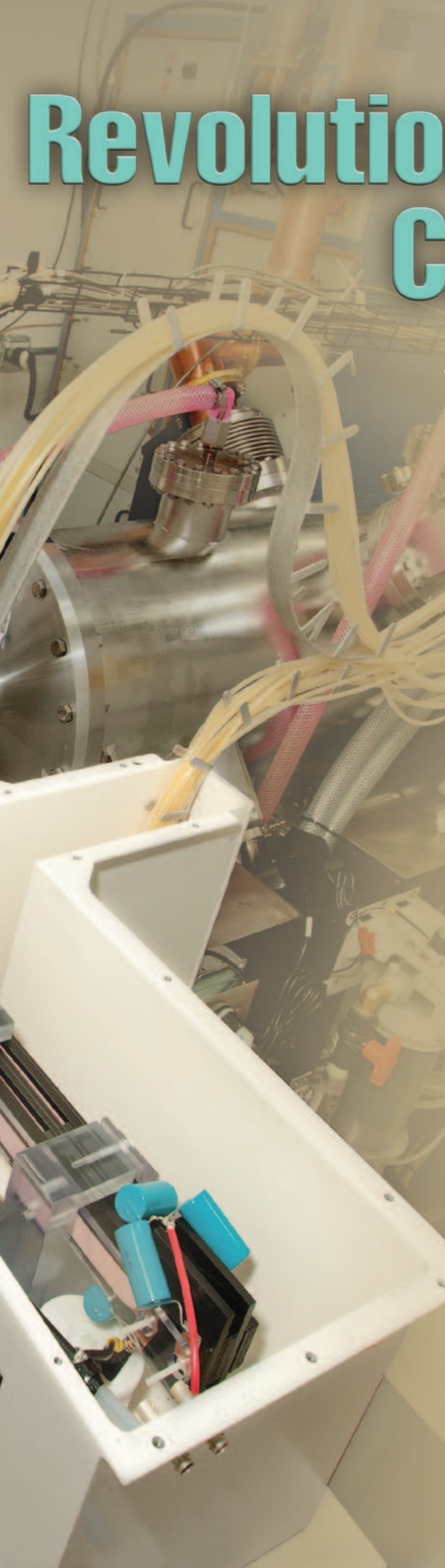
Multidisciplinary "team science" is a hallmark of all national laboratories and Lawrence Livermore in particular. It is the way we have pursued research since the Laboratory was established nearly 60 years ago. Working in partnership with many institutions, we continue to deliver innovative products that enhance national and global security and meet the evolving challenges facing Americans.

■ Thomas F. Gioconda is deputy director of Lawrence Livermore National Laboratory.

Weapons Diagnostics Technology

Revolutionizes Cancer Treatment

A Livermore technology transfer is a classic case of swords into plowshares.



At Compact Particle Acceleration Corporation (CPAC) in Livermore, California, a proton therapy system based on Livermore technologies is being developed to treat cancer patients. Anthony Zografos (left), general manager of CPAC, and Yoko Parker (right) stand alongside the dielectric wall accelerator prototype system. A radio-frequency quadrupole and proton source are to the right of the accelerator. In contrast, existing proton treatment centers are about the size of a basketball arena.

IN 2014, a particle accelerator born out of the Laboratory's nuclear weapons program may begin to appear in hospitals to deliver lifesaving proton therapy to cancer patients who would otherwise receive traditional and often dangerous radiation treatments. The path to this success has been long and challenging, but the payoff for patients is enormous.

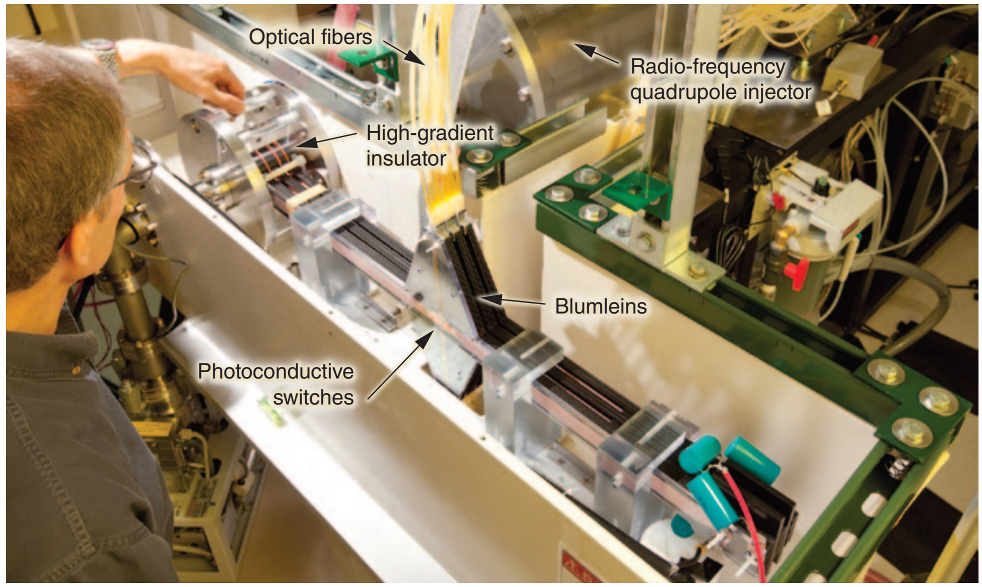
Scientists recognized the benefits of radiation as a method for treating cancer in the late 1800s, even before x rays were used as an imaging device. A medical student, Emil Grubbe, noted that his hands peeled when exposed to x rays and recognized x rays as a possible way to remove damaging tissue. Grubbe's use of x rays to treat a woman with advanced breast cancer slowed the tumor's growth. Today, radiation therapy can be a highly successful method of treatment, but it also often damages healthy tissue around the tumor as the radiation beam passes through the body. Ever more sophisticated methods of delivering radiation have reduced collateral damage, but it is still virtually impossible to avoid.

Enter proton therapy, whose properties are entirely different from x- or gamma-ray treatments. Because of their relatively large mass, protons have minimal lateral side scatter in the tissue. The proton beam is highly focused on the tumor and creates only low-dose side effects in surrounding tissue. A proton beam of a given energy has a certain range, allowing only very few protons to penetrate beyond that distance. Calibrating the energy of the beam to the depth of the tumor delivers the appropriate proton dose specifically to the tumor. Tissue closer to the surface of the body, above the tumor, receives less radiation and therefore less damage, while tissue around the tumor receives almost no protons. Proton therapy is considered especially effective for the treatment of eye cancer and for children who require radiation. It is also gaining ground as a method for treating prostate cancer because damage does not occur in the surrounding nerves that are important for maintaining sexual function.

Despite the effectiveness of proton therapy, only 31 proton treatment centers exist in the world, with just nine in the U.S. The current delivery method requires what is essentially a giant bunker to house a cyclotron or synchrotron and patient treatment rooms. The beamline, weighing several hundred tons, is surrounded by concrete walls 3 meters thick to shield patients and operators from the heavy dose of neutrons that are a side effect of beam loss in such systems. Three-meter-thick walls must also surround each therapy room, which are typically three stories high to accommodate the gantry vault that the patient lies in. Given that a proton treatment center is about the size of a basketball arena and costs more than $100 million, it comes as no surprise that few hospitals can afford one.

The proton therapy system based on Laboratory technologies and being refined by Compact Particle Acceleration Corporation (CPAC) of Livermore, California, will revolutionize proton delivery. The 4-meter-long linear accelerator will use intensity-modulated proton therapy to treat the patient and will be available for a small fraction of the cost of today's systems. The system will deliver protons more directly to the patient than do typical scattered proton beams and may require no more shielding than an ordinary x-ray facility. Given the projected low cost of the system and proven effectiveness of protons for the treatment of many cancers, hospitals will be more likely to retrofit one or more of their traditional radiation facilities to deliver protons instead.

In June, when CPAC completed the construction of its first precommercial prototype system, the company had taken a major step toward providing the world's most precise and compact proton accelerator for treating cancer and other solid tumors. Anthony Zografos, CPAC general manager, says, "The Laboratory has been an excellent partner for us. Livermore researchers, who are extremely knowledgeable about the technology, have assisted us in our efforts to improve the system. This CRADA [Cooperative Research and Development Agreement] has been a great success."



Livermore physicist George Caporaso works on the dielectric wall accelerator assembly at CPAC. The metal cylinder (top right) contains the radio-frequency quadrupole injector.

Present at the Creation

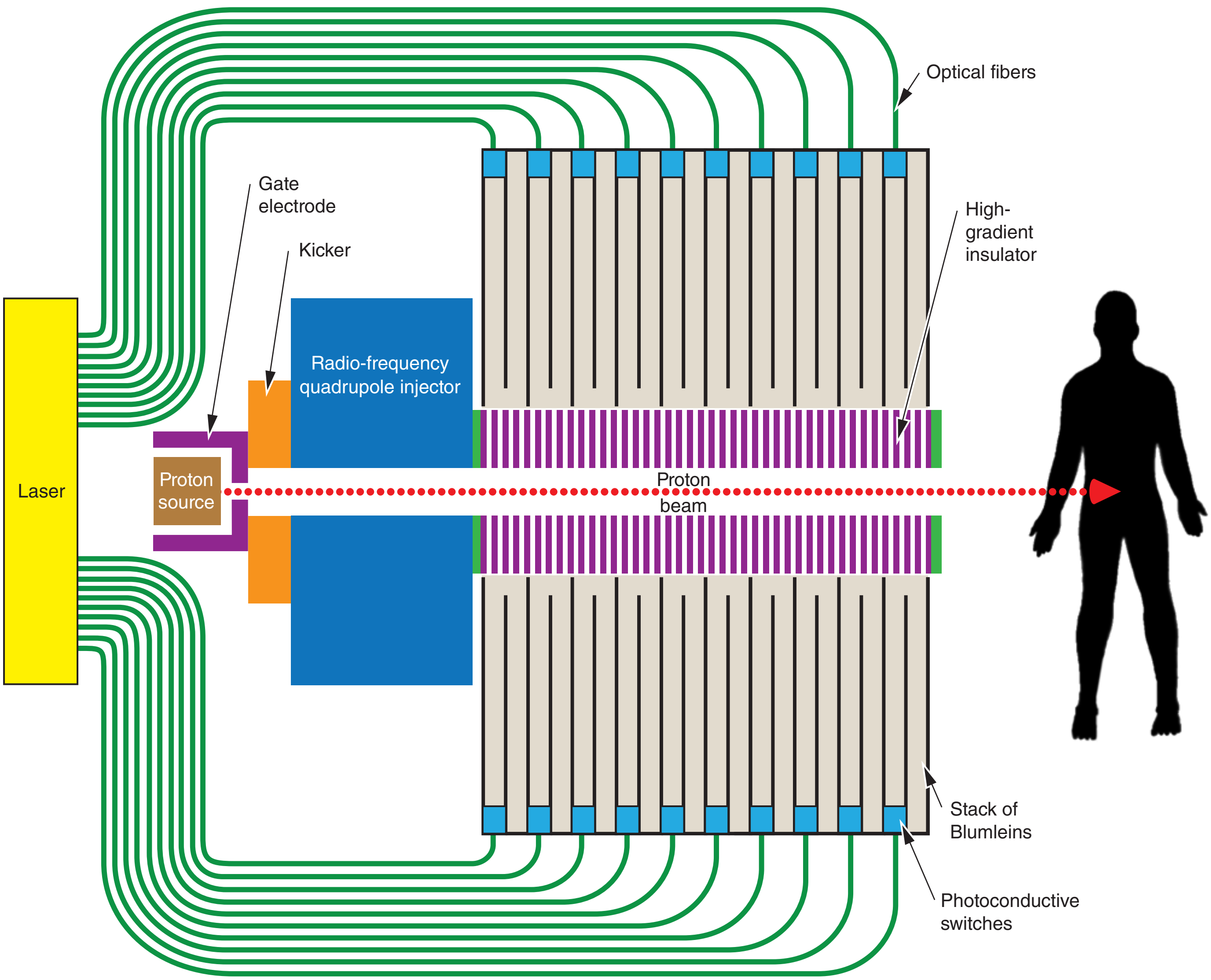
The idea for the compact proton accelerator came from a team, led by physicist George Caporaso, in Livermore's Beam Research Program in the Physical and Life Sciences Directorate. The program's responsibilities include the development of advanced accelerators and technologies. The novel design came about because of the potential benefits of performing x radiography with a small electron accelerator to augment the radiographic capabilities of Livermore's Flash X Ray (FXR) and Los Alamos National Laboratory's Dual-Axis Radiographic Hydrodynamic Test (DARHT) facilities.

FXR and DARHT are enormous machines, tens of meters long, and use a Livermore-developed linear induction accelerator to take x-ray images of very dense, nonnuclear test devices as they implode. Both systems are essential tools of the National Nuclear Security Administration's Stockpile Stewardship Program, which, in the absence of underground nuclear testing, must ensure that the nation's existing warheads remain safe, secure, and reliable well into the future.

An induction accelerator comprises a series of electrically independent modules, each pulsed in turn to push energetic particles forward, increasing their energy with every pulse. FXR and DARHT are long because they need to deliver photons at very high energies and because their acceleration gradient, the rate of energy increase over distance, is low, less than 1 megaelectronvolt (MeV) per meter. A method was needed to vastly increase the acceleration gradient and deliver equivalent energies across a distance of just a few meters.

The solution was a high-gradient insulator (HGI), a "sandwich" made from very thin layers of insulating and conducting materials across which large electric fields are applied to accelerate charged particles. HGI, which won an R&D 100 Award in 1997, forms the beam tube of a dielectric wall accelerator (DWA). "HGI was invented by an engineer at Sandia [National Laboratories] and was brought to our attention by Steve Sampayan, an engineer in our group who had worked at Sandia," says Caporaso. But Sampayan and his team took the invention to new lengths, so to speak. Livermore's HGI is constructed from conducting layers made of metal, such as stainless steel, alternating with insulating layers of plastic, such as polystyrene.

The small-scale induction accelerator comprises a stack of HGIs that can hold extreme voltages. A particle injector starts the action, and transmission lines made of dielectric materials and embedded conductors produce the electric field that propels the charged particles forward in the tube. The transmission lines are



This schematic illustrates the flow of protons from a source through the dielectric wall accelerator assembly to a patient. A commercially available ion source sends protons into a "kicker" that injects pulses of protons into a radio-frequency quadrupole, which compresses the protons into short bunches. Switches along the accelerator open and close at high speeds to control the voltage and increase the energy of particles zooming down the accelerator. Careful control of the switching mechanisms creates a beam pulse with the speed, form, amplitude, and length needed for a particular patient.

called Blumleins, after a technology developed by the prolific British inventor Alan Blumlein, who also developed stereophonic sound. A laser delivers power to switches in the Blumleins through an optical-fiber distribution system. The tiny, solid-state silicon carbide optical switches on the Blumleins open and close at high speeds to control the high-power voltage that fires each Blumlein, thereby increasing the energy of the particles as they traverse the tube.

With the opening and closing of each switch, one section at a time of DWA is energized, creating a "virtual traveling wave" that pushes the energized particles down the tube. Caporaso likens the phenomena to "the wave" that sports fans perform around a stadium. The ones standing are pushing the particles. They sit down and their neighbors continue the push. One thousand Blumleins may be fitted around a 2-meter tube, each one fired on command to control the speed, form, amplitude, and length of the beam pulse.

"If the whole tube were energized at once," says Caporaso, "it would short out. But that problem is solved by energizing only a very small area of the tube at a time." This method also places less stress on materials in the device.

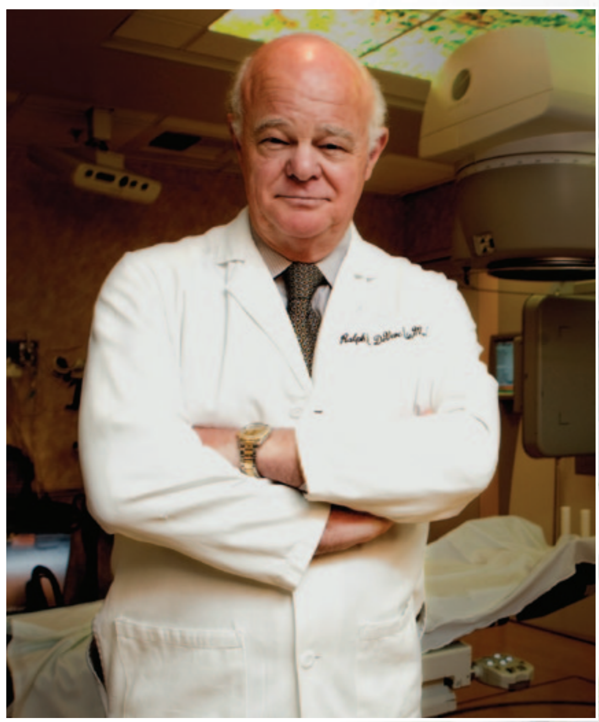
The DWA components were integrated into an accelerating module for radiography, but a complete accelerator was not built because the weapons application was not pursued. However, at about that time, fellow physicist Dennis Matthews asked Caporaso if DWA could deliver protons instead of electrons. Matthews was leading a team developing biomedical devices at the Laboratory and also working at the newly established University of California (UC) Davis Cancer Center, in which Livermore was an active collaborator. Matthews knew that Ralph deVere White, a urological oncology specialist and director of the center, was on the hunt for a more compact method for proton therapy.

Compact Accelerator Comes to Life

Both Matthews and deVere White were excited about the prospects for Livermore's novel electron delivery methodology. However, much work remained for DWA to be modified for use as a proton delivery medical device. The components developed for radiography had been designed to deliver electrons in long pulses at approximately 10 million volts per meter. But effective proton therapy required very short pulses and a gradient of at least 40 million volts per meter.

In 2004, the Laboratory Directed Research and Development Program funded a project to determine the feasibility of DWA technology for medical use. Later, UC Davis invested millions of dollars, confident that the DWA technology would be the effective, compact proton therapy device so needed by the oncology community. Matthews notes that the goal of this project was to prove the technology's value and make it attractive to investors, without whom DWA for proton therapy would never get beyond the Laboratory gates.

It proved to be attractive enough for TomoTherapy, Inc., a company headquartered in Madison, Wisconsin, and already active in the development



Ralph deVere White, director of the University of California (UC) Davis Cancer Center, was instrumental in UC Davis partnering with the Laboratory to pursue a compact proton therapy device needed by the oncology community. (Courtesy UC Davis Cancer Center.)

and sale of traditional radiation treatment systems. In a 2007 technology transfer agreement, TomoTherapy entered the proton therapy business with funding for the continued development of the new accelerator. Several TomoTherapy researchers joined the Laboratory team. With TomoTherapy's financial and personnel backing, Livermore was able to develop and successfully test a prototype in December 2007, of which the DWA portion was about 2 centimeters long. According to Livermore engineer Jim Watson, who has been a member of the DWA team since 2007, this test proved the world's first compact DWA accelerator, with particle injector and diagnostics. By December 2008, the team had demonstrated that the device could accelerate protons.

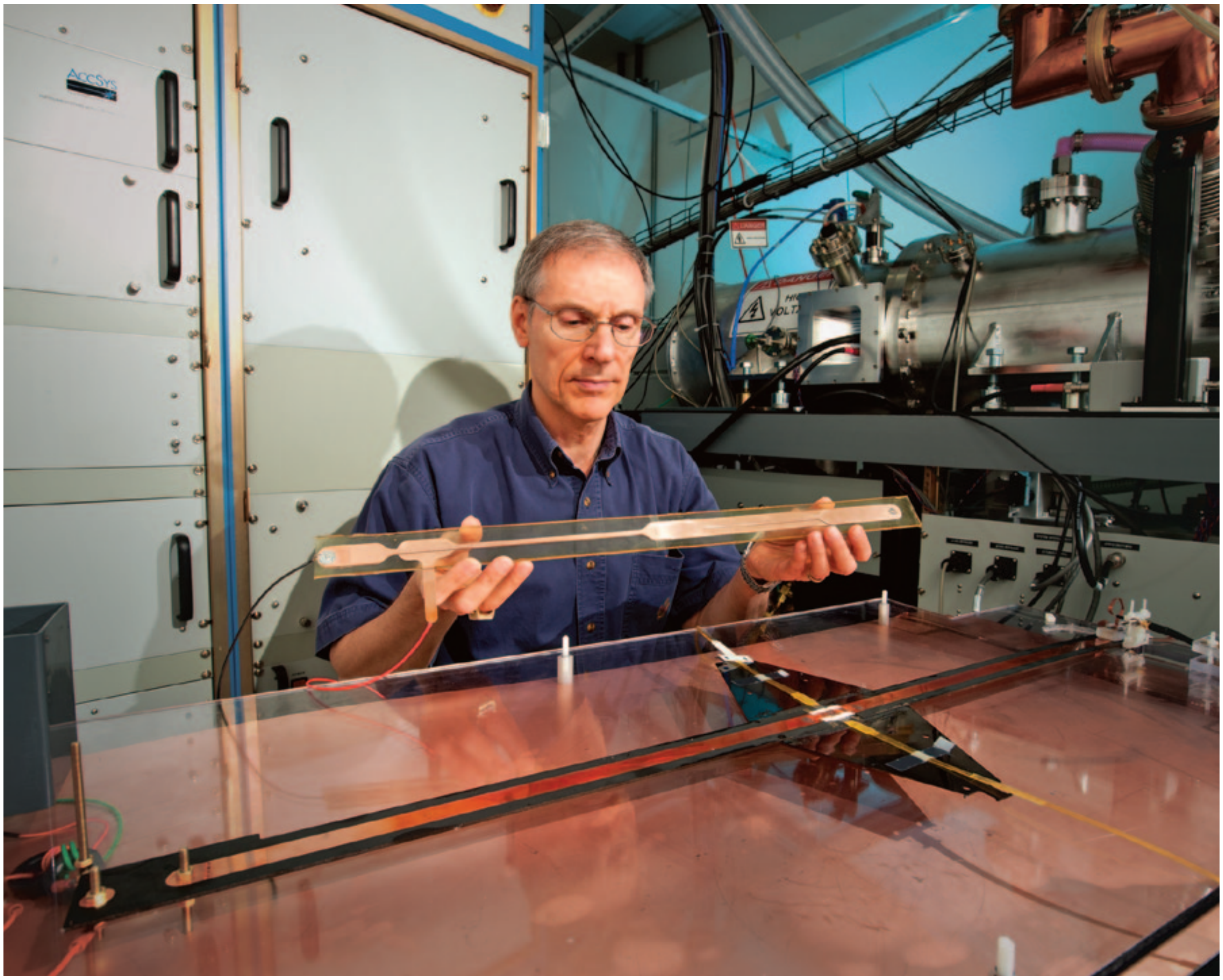
DeVere White notes that this technology is unique for proton therapy. No other company is close to delivering a device with the small size, low cost, and treatment effectiveness of DWA. Says deVere White, "Some cancer experts wonder whether the $150 million price tag is worth the advantages that proton therapy can provide. This solution takes the cost issue away."

CPAC Enters the Picture

In 2008, TomoTherapy announced its participation in the new venture CPAC, located just blocks from the Laboratory in Livermore. In 2009, Zografos, who has considerable medical technology experience, was hired and began to build his staff of engineers and other experts to refine the transferred technology. Today, CPAC has 10 employees. "In addition, a number of Laboratory staff are in and out almost constantly assisting us," says Zografos. Teams of experts on a technical advisory board and a clinical advisory board also support CPAC. Rock Mackie, cofounder of TomoTherapy, is chair of the clinical advisory board.

Zografos notes that except for the Livermore-designed accelerator, all components are commercially available and almost all are from manufacturers in California. "Our entire effort here at CPAC is on the accelerator," he says. "The development of the rest of the system, including the laser, high-voltage equipment, and fiber optics, is outsourced." One decision made early on was whether to use Livermore's particle injector or a commercial radio-frequency quadrupole (RFQ). The prices were the same, but the technical advisory board chose the commercial product.

The first system test in March included a pulser composed of a commercial ion source and a 2-MeV RFQ that serves as an injector for delivering subnanosecond protons into DWA. Both pulser components are conventional, proven technologies. In addition, a novel 1-centimeter "kicker" between the ion source and RFQ acts as a gate to inject a single pulse of protons into the quadrupole. RFQ then compresses these protons into a bunch about 200 picoseconds long when exiting. Physicist Gary Guethlein led a small team to develop the compact kicker. Guethlein and physicist Steve Falabella also created a timing system built of commercially available components to synchronize RFQ with the



Caporaso examines CPAC's newest Blumlein design. Tests at CPAC are combined with computer simulations at Livermore to produce a practical design.

kicker and DWA switching laser. Protons are thus in DWA only as needed and with almost no jitter.

As development of the accelerator progresses, Caporaso continues to lead Livermore's work. Guethlein visits CPAC often to assist with testing and design. Another frequent visitor is physicist Yu-Jiuan Chen, who is responsible for optimizing the delivery of protons. As such, she plays a major role in specifying design requirements for the Blumleins, the high-gradient insulator, the optical switch, and other parts of the accelerator. If the commercial components are not ideal, her task is to combine them into a workable design.

Chen notes that while the switch design is final, she, Brian Poole, and others are still working on the Blumleins, combining tests at CPAC with computer simulations at Livermore. The Blumlein's structure is critical because it determines the form, length, and amplitude of the pulse. "Currently, each Blumlein is 2 millimeters thick," she says. "Thinner is better to maximize the acceleration gradient. A thicker Blumlein dilutes the gradient."

To test the insulator, CPAC has installed a high-voltage pulser in an electromagnetically shielded chamber at its facility. Various configurations, materials, and fabrication methods for the insulator are examined to determine the combination that can best withstand the high gradients. Livermore and CPAC staff work together on the tests, and Chen's team performs simulations that aid experimentation. The Laboratory's Watson is often at CPAC as well, helping with testing of HGI and other engineering functions.

Chen says, "Little room exists for external focusing lenses in the short length of the accelerator, which would help keep the beam's 'spot size' small and tightly focused." Dealing with this challenge requires such tasks as developing focusing methods that provide simultaneous longitudinal and transverse stability, flattening the accelerator waveform to reduce radial defocusing, and maintaining beam quality. The phase of the first Blumlein firing has to match that of the proton source, and the phase velocity of Blumlein firings must match the proton velocity throughout the accelerator. Thanks to the kicker and timing system, those parts of the accelerator are in synch. Diagnostic devices designed by Guethlein and Falabella are installed along the length of DWA about every meter to ensure beam quality. Above all, says Chen, "We have to produce a practical design."

"The first prototype, tested this spring with a DWA of about 5 centimeters, proved our ability to accelerate protons," says Zografos. With subsequent tests, more modules will be added, lengthening the accelerator.

The accelerator for the second prototype will be about 20 centimeters long. That unit, scheduled for testing in the first quarter of 2012, will prove the clinical viability of the device. This prototype will not be used for treatment but rather to demonstrate that adding more modules does indeed increase output energy and that the machine can be scaled up to the energy levels needed to deliver therapeutic protons. According to Livermore simulations, a 4-meter accelerator would deliver 160 MeV with clinical precision. A shorter, 2-meter accelerator would deliver 120 MeV.

The third and final prototype, scheduled for testing in 2013, will combine both technical and clinical viability in an integrated system that could be installed in hospitals. Says Zografos, "We have to know whether the device can be reasonably priced and what the cost of ownership will be in terms of maintenance, spare parts, and so on."

Accuray, Inc., which acquired TomoTherapy in June, will likely handle final integration of all the system components. Clinical testing may take place at the University of Wisconsin at Madison's hospital, although the testing location has yet to be finalized. Approval for patient use by the Food and Drug Administration will be relatively simple because proton therapy already has the agency's approval. This particular system need only prove that it can deliver protons at therapeutic levels.

Accuray–TomoTherapy will also likely be responsible for the manufacture, sale, and distribution of this lifesaving device to hospitals. To facilitate a hospital's transition from x- and gamma-ray treatment to proton therapy, CPAC will deliver a fully integrated product that allows a hospital to easily begin implementing proton therapy. The system will incorporate treatment planning, quality assurance software and tools, volumetric computed tomography imaging, beam delivery, and patient positioning.

Lasting Relationships

CPAC holds the exclusive commercial rights to more than 30 DWA-related patents or patent applications and has the license for nonmedical uses for the optical switches and DWA. "The technology could be used for imaging and cargo inspection, for example," says Zografos. Both are high on the Department of Energy's list of important national security projects, so Livermore involvement will surely continue.

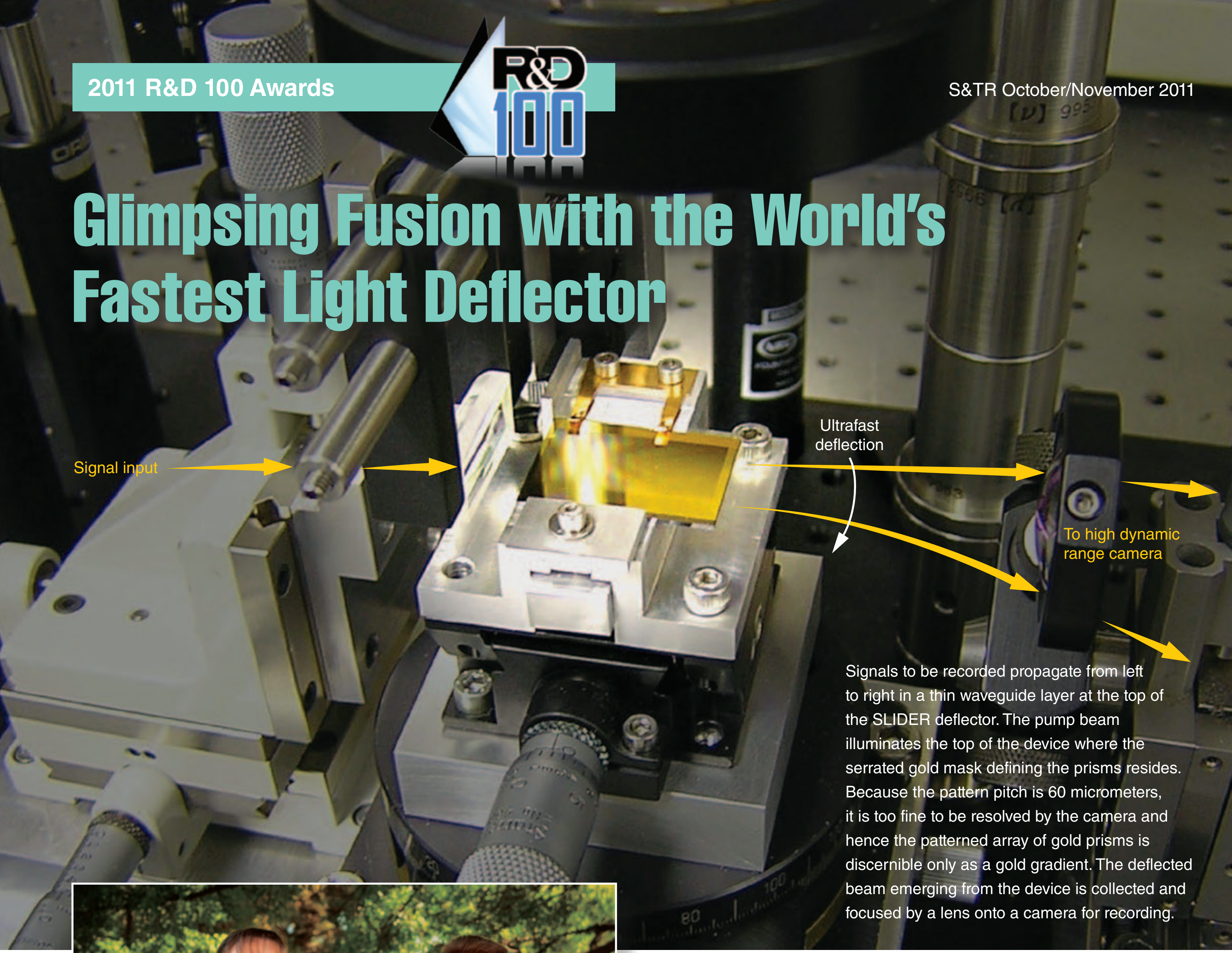
DeVere White observes that the Laboratory's application of a stockpile stewardship technology to the medical field is a highly effective use of tax dollars. "It leverages monies spent on national security without diverting the Laboratory from its primary mission," says deVere White. "Without Livermore, the Cancer Center, TomoTherapy, and CPAC, this technology for cancer treatment would not exist. Cancer patients will be the beneficiaries of an exceptional partnership."

—Katie Walter

Key Words: Accuray, Inc.; cancer treatment; Compact Particle Acceleration Corporation (CPAC); Cooperative Research and Development Agreement (CRADA); dielectric wall accelerator (DWA); high-gradient insulator (HGI); proton therapy; x-radiation therapy; technology transfer; TomoTherapy, Inc.

For further information contact George Caporaso (925) 422-7852 (caporaso1@llnl.gov).

Glimpsing Fusion with the World's Fastest Light Deflector



Signals to be recorded propagate from left to right in a thin waveguide layer at the top of the SLIDER deflector. The pump beam illuminates the top of the device where the serrated gold mask defining the prisms resides. Because the pattern pitch is 60 micrometers, it is too fine to be resolved by the camera and hence the patterned array of gold prisms is discernible only as a gold gradient. The deflected beam emerging from the device is collected and focused by a lens onto a camera for recording.

The Livermore development team for the serrated light illumination for deflection-encoded recording system (SLIDER): (from left) Susan Haynes and John Heebner.

FUSION, the world's great promise for a source of clean and virtually limitless energy, could replicate the very process that powers the stars to meet our most pressing needs on Earth. Lawrence Livermore's National Ignition Facility (NIF) is conducting experiments aimed at achieving fusion ignition and energy gain, the process whereby more energy is released than is required to initiate the fusion reaction. To better understand the physics of fusion and determine the minimum laser input energy needed to start the fusion process, researchers need to acquire accurate details of the burning plasma inside fusion targets. Recording such data with both fine time resolution and high dynamic range, however, presents enormous challenges for existing instruments given the trillionths-of-a-second time frames at which these reactions will occur.

A novel solid-state optical device developed at the Laboratory by engineers John Heebner, Susan Haynes, and Chris Sarantos (formerly of Livermore) may provide a solution to the problem.

The serrated light illumination for deflection-encoded recording (SLIDER), recently honored with an R&D 100 Award, is the world's fastest light deflector. When mated to an ordinary camera, it can record optical signals on picosecond (trillionth of a second) timescales. When combined with a high dynamic range camera, SLIDER can maintain this high temporal resolution and a high dynamic range—two performance parameters that are difficult to meet simultaneously.

This unique combination of high resolution and dynamic range will be crucial for better understanding reactions that occur under the extreme conditions—such as temperatures of more than 100 million degrees Celsius—needed for the tritium–deuterium fuel to "ignite" in a NIF target and undergo thermonuclear burn.

"We're in the infancy of trying to understand the fusion process," says Heebner, likening the effort to that of devising the internal combustion engine more than 100 years ago, both in terms of its potential to revolutionize human society and the challenges faced during its development. Scientific advances at all levels, he explains, rely not only on great ideas but also on access to the right instruments.

"Fusion reactions at NIF will last only several tens of picoseconds," Heebner says. "At such a brief timescale, the availability of commercial instruments to record these signatures with high fidelity is extremely limited or nonexistent. We thus have to develop our own tools." Initial efforts for this work were funded by Livermore's Laboratory Directed Research and Development Program.

Overcoming Limitations of Existing Technologies

Oscilloscopes represent the majority of commercial high-speed recording instruments used to capture extremely short-lived signals. Electron-beam-based streak cameras offer the ability to record even finer details. These instruments use electric fields to sweep electron beams, much like in cathode-ray-tube television sets. They can record data at picosecond timescales but are inherently limited by what are known as space-charge effects—the signal blurring that inevitably occurs when charged particles repel each other. The stronger the signal, the worse the blurring effect and, therefore, the more limited the instruments' useful dynamic range.

Enter SLIDER, whose beam consists not of charged electrons but of uncharged photons. The underlying idea is not new. Scientists have used optical beams to avoid the space-charge effect for decades. But it took what Heebner calls "a flash of insight" to devise an optical version of the streak camera that has the capability of deflecting light rapidly enough to achieve picosecond resolution.

While the signals from fusion reactions are too fast to be recorded by conventional electronic instruments, they are also too slow for spectral techniques now being used in ultrafast laser physics with characteristic timescales of femtoseconds. "SLIDER complements existing technologies and bridges the gap between conventional streak cameras and spectral-based ultrafast recording techniques," Heebner says.

It's All in the Prisms

At the heart of SLIDER lies a solid-state optical deflector that rapidly activates an array of prisms for each sweep repetition. The signal to be recorded rides on a beam of light sent through a 1-centimeter-wide semiconductor planar waveguide that is less than 1 micrometer (1 one-hundredth the width of a human hair) in height. A separate pump laser directed in from above rapidly modifies the waveguide's optical properties. The pump beam is first passed through a serrated mask just above the waveguide. While the signal is traversing the waveguide, the patterned pump beam imprints an array of more than 100 prisms.

At this point, time of flight does the rest. Because the earlier portions of the signal have advanced farther along the waveguide at the moment of prism creation, they are deflected the least. The later portions, however, see more activated prisms and are hence deflected the most. This sweeping beam is then collected and focused by lenses for recording on a conventional camera. The waveguide and serrated pattern are created using ordinary semiconductor growth techniques and contact photolithography, making the SLIDER deflector fabrication relatively inexpensive.

SLIDER can be used to monitor the brilliant x-ray bursts streaming from NIF fusion targets using radiation-to-optical encoders, also developed at the Laboratory, inserted in front of the device. In addition to its application in fusion energy science, SLIDER might be used to characterize high-bandwidth, long-haul telecommunication systems, chemical reactions, particle accelerators, and short-pulse lasers.

The development of fusion energy is one of the most difficult science and engineering challenges ever undertaken. Scientific insights, however, often depend on access to better diagnostic instruments. The insights this new technology will provide may help the Laboratory achieve this grand challenge and advance scientific knowledge across many disciplines.

—Monica Friedlander

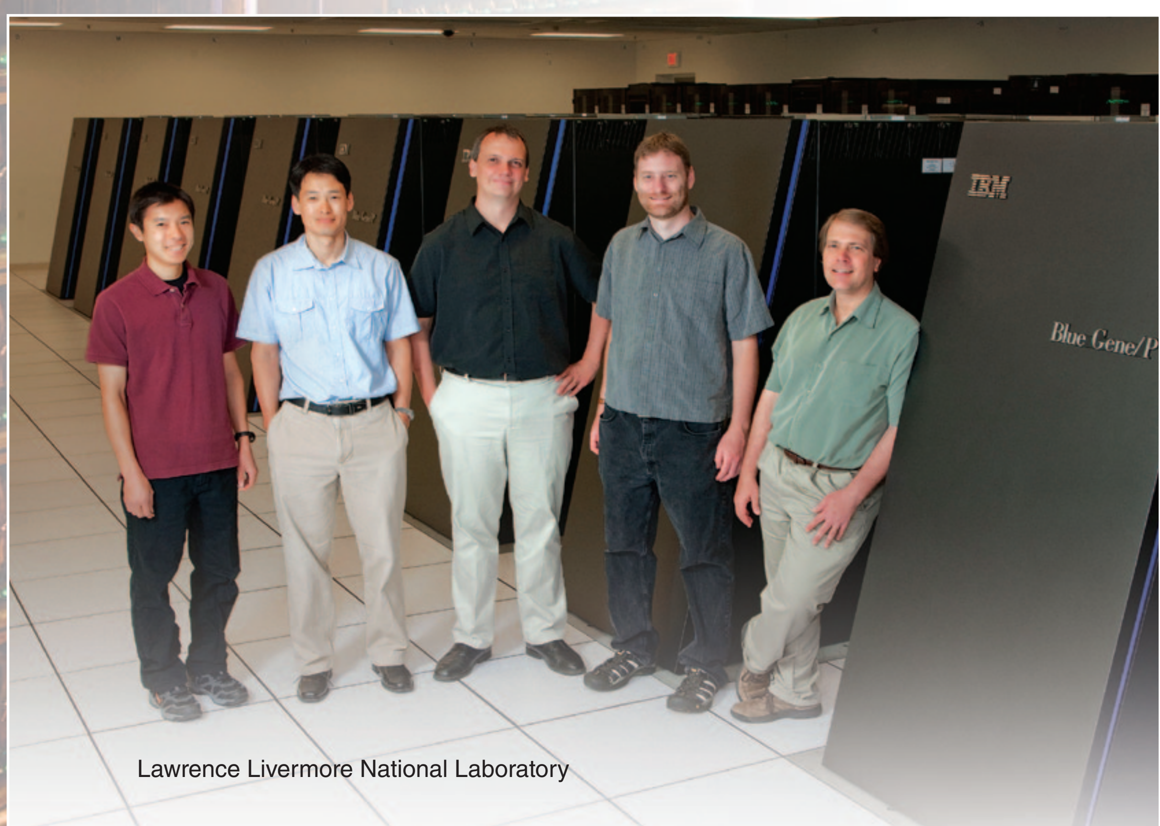
Key Words: fusion, laser, National Ignition Facility (NIF), optics, R&D 100 Award, radiation-to-optical encoder, serrated light illumination for deflection-encoded recording (SLIDER).

For further information contact John E. Heebner (925) 422-5474 (heebner1@llnl.gov).

Lightweight, Scalable Tool Identifies Supercomputers' Code Errors

CONSIDER the common desktop computer. The hardware that runs all of an application's many independent execution units, or processes, is called a core. Most desktops have between one and four cores. These computers cost between a few hundred and a few thousand dollars. In contrast, today's largest supercomputers contain hundreds of thousands of cores and cost hundreds of millions of dollars. The scientific applications these computers run—which often culminate from decades of multiperson development efforts—are equally costly. Single faults, or bugs in the codes, that disable only one process can halt an application's execution. During the resulting debugging process, developers use up their time locating the bugs, with delays consuming machine hours and racking up significant costs.

Extreme-scale systems present an additional hurdle. Current debugging tools were never designed to scale to such sizes. Therefore, at scales of a thousand processes, these tools can take minutes to perform a single debugging operation, and typically, each operation is performed tens to hundreds of times during just one debug session. "Our debugging tool is our response to this problem," says computer scientist Greg Lee. Lee and fellow Livermore computer scientists Dong Ahn, Bronis de Supinski, Matthew LeGendre, and Martin Schulz, with collaborators at the University of Wisconsin at Madison and the University of New Mexico, designed and developed a unique R&D Award–winning solution called the stack trace analysis tool (STAT). The tool can identify errors in code running on today's largest machines. It will also work on the even larger machines expected to roll out over the next several years.



"The approach of other debuggers provides so much detailed information about each process that they are inherently unusable at such extreme scales," says Lee. STAT, on the other hand, was designed to provide meaningful information quickly. "Just as medical staff can call 'STAT' to get immediate action and help patients in distress, when users of supercomputers need to debug an application at extreme scales, they can call on STAT," says Lee.

Getting Help STAT

Errors in computer codes arise not only in the initial development phase of applications, when the code is beginning to take shape, but also when new features are added to mature software. These bugs sometimes lay dormant even in heavily tested and widely used codes, only to emerge when run with a new data set, on a new platform, or at larger scales. Scientific codes designed for high-performance computing systems provide additional challenges because their complex codes incorporate multiple mathematical and scientific software libraries.

STAT works by detecting and grouping similar processes at suspicious points in an application's execution. It quickly and automatically identifies anomalies and outliers—processes that cannot be grouped or whose behavior is substantially different—because they often indicate flawed execution. STAT achieves this grouping by dynamically examining the state of each process and extracting the call stacks—the sequence of function calls—that led to the current point of execution. In this way, STAT can relate the state of the processes to each other.

Speed Daemons

STAT offers varying levels of detail in the call stacks, from coarser function granularity to specific source-code line numbers. Because it gathers stack traces across the entire application, it provides a global view of what every process is doing. These stack traces are merged to reduce the problem search space, so users can identify a small yet representative subset of tasks on which to apply heavyweight analysis.

Another important scaling advantage that STAT has over similar tools is its lightweight design, which allows the tool to maintain interactive response times. Most scientific applications make full use of all available processing power and memory capacity, which leaves few resources for tools. STAT's daemons—tool processes that run alongside the application—have very low computational and memory requirements.

Pinpointing Problems

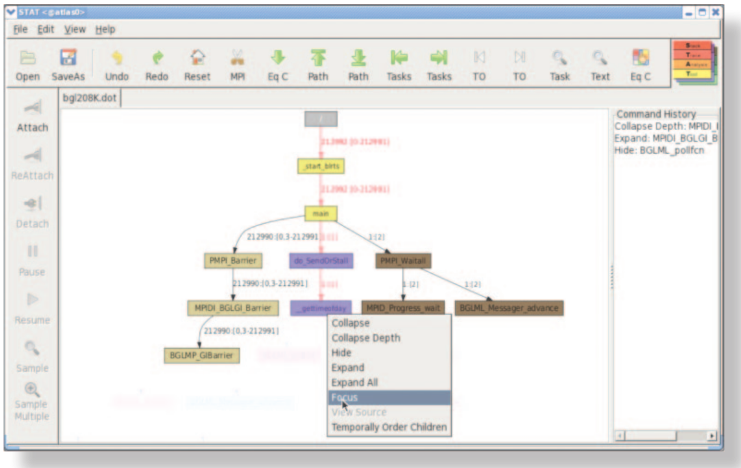
STAT can not only distinguish a process that is stuck in a single location in the code but also pinpoint the exact task causing the hang. STAT also derives the relative execution progress of each application task, which is useful for determining problematic application processes. "A culprit may have made the least execution progress through the code because it's stuck in a computation phase that the rest of the application processes have already passed," Lee says.

The tool has run on a wide range of supercomputer platforms, including the IBM BlueGene family of machines and several of the world's fastest as reported by the Top500 Supercomputer Sites list. STAT also runs on the Cray XT and Cray XE high-performance computers and has been demonstrated at 216,000 cores on Oak Ridge National Laboratory's Jaguar system, which once reigned as the fastest supercomputer. STAT was recently run to discover a bad node on IBM BlueGene/L. "In this case, STAT definitely proved itself useful," says Lee. "At best, finding this problem would have bordered on impossible without STAT."

The team is excited about the recognition and publicity the award will bring and looks forward to helping others adopt the tool. In the future, the scientists hope to complete their research and turn STAT over to a company for commercialization.

—*Kris Fury*

The Livermore development team for STAT: (from left) Greg Lee, Dong Ahn, Martin Schulz, Matthew LeGendre, and Bronis de Supinski.

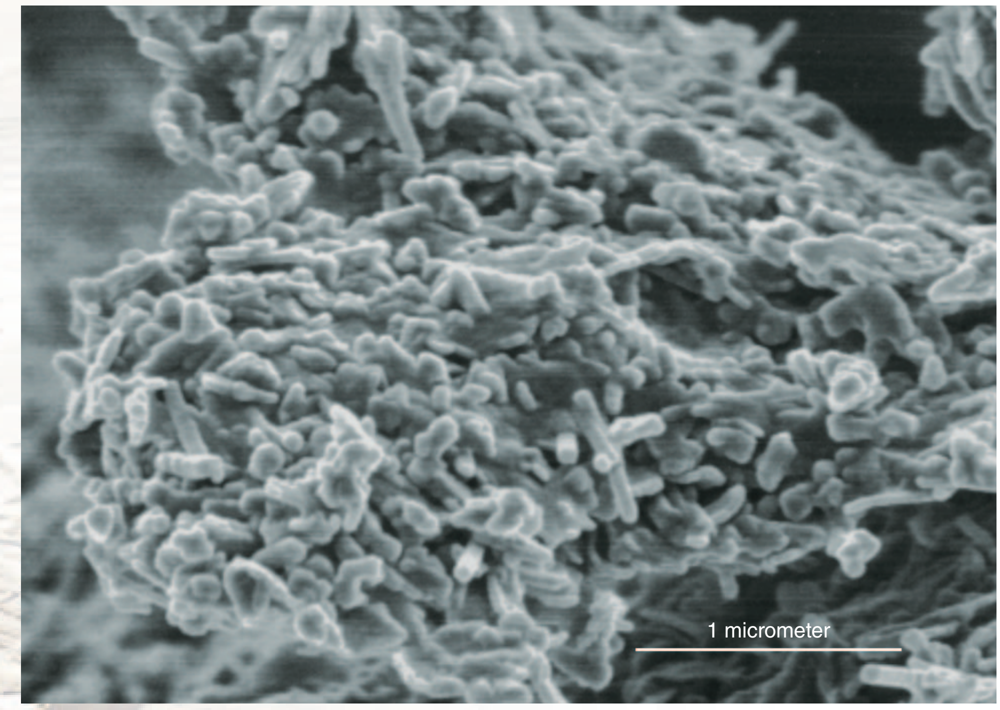


The stack trace analysis tool (STAT) includes a powerful and intuitive graphical user interface that allows the user to identify quickly where a bug exists in an application. STAT automatically analyzes the state of the application and pinpoints potential bug locations.

Key Words: bug, computer core, debugging, extreme-scale computing system, high-performance computing, R&D 100 Award, stack trace analysis tool (STAT).

For further information contact Greg Lee (925) 424-6554 (lee218@llnl.gov).

Plutonium Hitches a Ride on Subsurface Particles



Livermore scientists are conducting field studies and microscopic experiments to determine how plutonium is transported in groundwater. Transmission electron microsope images such as the one shown above allowed the researchers to examine colloids taken from groundwater at the Nevada National Security Site (in the background). These studies and others have confirmed that colloids play an important role in transporting plutonium at contaminated sites worldwide.

FOR decades Lawrence Livermore researchers have worked to obtain a detailed understanding of the actinides, a group of 14 radioactive elements that includes plutonium and uranium. The long-standing research is driven by the Laboratory's historic roles in assessing the nation's nuclear stockpile, ensuring the safe storage of nuclear waste, and evaluating the fate and transport of radionuclides in the environment.

Environmental contamination by radionuclides, particularly actinides, is a serious concern at several Department of Energy (DOE) facilities, including the Hanford Site, the Nevada National Security Site (formerly the Nevada Test Site), and the former Rocky Flats Plant, as well as at a number of contaminated sites worldwide. Although concentrations of most of the actinides transported from the original source location are detected at levels below regulatory dose limits, actinides' long half-lives combined with their high toxicity make them of particular concern.

A five-year experimental effort involving about a dozen Laboratory scientists and their collaborators is examining the geochemical processes that control plutonium's sometimes baffling behavior in the ground. The researchers' goal is to gain sufficient understanding of the processes that control plutonium's behavior so they can more accurately predict long-term transport.

"We want to provide decision makers with the scientific basis to support plans for the remediation and long-term stewardship of legacy sites where plutonium contamination occurred," says Livermore geochemist Annie Kersting, leader of the plutonium transport effort and director of the Livermore branch of the Glenn T. Seaborg Institute, one of the world's leading centers for actinide research. Other Livermore researchers include lead scientist Mavrik Zavarin, Susan Carroll, Zurong Dai, Ross Williams, Scott Tumey, Pihong Zhao, Ruth Tinnacher, Patrick Huang, Harris Mason, James Begg, and Ruth Kips. Collaborators include Brian Powell (a former Livermore postdoctoral researcher) from Clemson University in South Carolina and Duane Moser from Desert Research Institute in Nevada. The group's research is funded by the DOE Office of Science's Biological and Environmental Research Program.

Plutonium Is a Perplexing Element

Scientists regard plutonium as one of the most complex and perplexing elements in the entire periodic table. For example, its transport in groundwater strongly depends on its oxidation state, and plutonium is one of the few elements that can exist in four unique oxidation states simultaneously. Plutonium has been shown to migrate while associated with small (less than 1 micrometer in diameter) particles, or colloids. It may also migrate while associated with mobile organic matter.

For many years, scientists had assumed that plutonium, because of its low solubility in water and its strong tendency to sorb (adhere) to soil and rocks, does not migrate. However, in 1999, Kersting and colleagues from Lawrence Livermore and Los Alamos national laboratories detected plutonium in groundwater at the Nevada Site. Isotopic signatures showed that it originated from a specific nuclear test conducted years earlier more than 1.4 kilometers away. The team found that the plutonium was associated with colloids in the groundwater. Since 1999, additional studies by this team and fieldwork by other scientists have confirmed that colloids play an important role in transporting plutonium at a number of other contaminated sites around the world.

Past laboratory experiments aimed at understanding how plutonium moves in the subsurface were performed at concentrations higher than those observed in the field. However, the dominant geochemical processes operating at higher concentrations may not be the same as those that occur in nature at much lower concentrations. New analytical tools developed at Livermore are providing an opportunity to conduct experiments at the much lower concentrations measured in nature. The extremely sensitive instruments allow researchers for the first time to mimic environmental conditions. Much of the Livermore team's focus is on determining how plutonium hitches a ride on colloids. These microscopic colloidal particles are found in all waters and can be composed of organic material, inorganic minerals (for example, clays), or microbes.

Kersting says it is important to capture processes such as colloidal transport of contaminants so that models can accurately estimate how much, how far, and how fast plutonium can travel. "Colloidal transport was originally not considered in most transport models. Now, researchers are trying to understand when colloids are important in transport and when they are not," she says. Currently, a basic understanding of how plutonium adheres to mineral colloids (and desorbs from them) is lacking. In particular, transport models suggest that the rates of sorption and desorption control colloid-facilitated actinide transport, but the factors affecting reaction rates have not been determined experimentally.

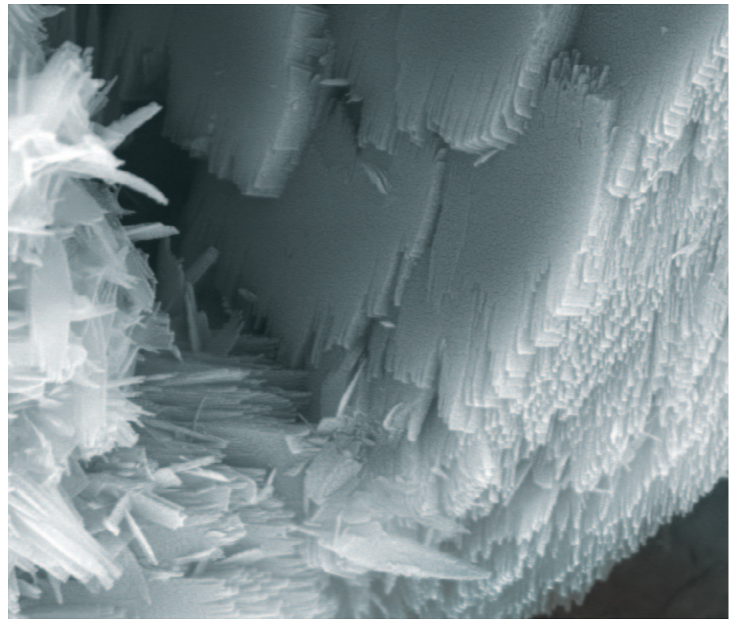
Sensitive Instruments Provide Unique Opportunity

Livermore instruments allow researchers to conduct experiments involving extraordinarily low (but environmentally realistic) levels of plutonium in the picomolar to attomolar range (10^{15} to 10^{18} moles per liter, with a 10^{18} concentration of plutonium being roughly equivalent to dissolving one grain of salt in 100 Olympic-size swimming pools). Instruments include the accelerator mass spectrometer at the Laboratory's Center for Accelerator Mass Spectrometry and the newest generation of inductively coupled plasma–mass spectrometers. With these extremely sensitive instruments, researchers can identify where the plutonium is sited on a microscopic colloid, determine how it was deposited on the colloid, and elucidate the geochemical processes controlling its mobility.

Plutonium-containing colloids are being characterized in terms of their inorganic, organic, and microbial associations by using a transmission electron microscope and a nanometer-scale secondary-ion mass spectrometer. The Livermore experiments entail reacting extremely low concentrations of plutonium with different materials such as mineral colloids, organic matter, and microbes, and determining to what extent changing parameters, such as pH and concentration, affect the interaction of plutonium with these substrates.

"The experiments show that each mineral colloid interacts with plutonium in a unique manner," says Zavarin. For example, one form of plutonium, nanocrystalline plutonium-4–oxygen-7 (Pu_4O_7),

Collaborator Duane Moser from the Desert Research Institute collects groundwater containing plutonium from the Nevada Site.



A scanning electron microscope image shows colloidal particles produced during the reaction of nuclear melt glass in groundwater at the Nevada Site.

readily precipitates on goethite, an iron oxide and a common constituent of soil. The team is examining the surface deposition of Pu_4O_7 to determine why plutonium molecules bind so tightly to goethite. The research indicates that plutonium surface precipitates become distorted as they are deposited, which apparently strengthens the bond between goethite and plutonium. In contrast, this process does not occur when plutonium interacts with quartz (silica dioxide), one of the many silicates found in soil.

The experimental results are being compared to samples taken from contaminated sites at Nevada, Rocky Flats, Hanford, and Russia's Mayak nuclear complex. Kersting notes that colloids may not play a major transport role at all sites and that the depositional geology and hydrology affect transport. "We're slowly filling in the scientific gaps," she says.

One undetermined factor is how microbes affect plutonium transport. Desert Research Institute scientists have collected microbes at the Nevada Site colocated with plutonium contamination, identified and cultured the microbes, and shipped them to Livermore for studying the interaction between plutonium and microbial communities.

Leveraging Research Results

Zavarin notes that other actinides are present at contamination sites, and the team's research results may also shed light on how these elements are transported. "We want to apply our resources to other actinides such as neptunium, americium, and uranium," he says. The research is also applicable for European scientists and decision makers who are planning the construction of facilities to store high-level waste from nuclear power plants. Kersting's team is collaborating with several international scientists in this effort.

An added benefit of the Livermore research is the opportunity for a new generation of actinide scientists to work with plutonium. Several postdoctoral researchers and summer graduate students are contributing to the research, with some participating in the Seaborg Institute's Nuclear Forensics Summer Internship Program, funded by the Department of Homeland Security. Thanks to the research, the most perplexing element on the periodic table is slowly losing some of its mystery about how it travels underground faster and farther than anyone at first expected.

—Arnie Heller

Key Words: actinide, Glenn T. Seaborg Institute, Hanford Site, Mayak nuclear complex, Nevada National Security Site, Nevada Test Site, nuclear forensics, plutonium, Rocky Flats Plant.

For further information contact Annie Kersting (925) 423-3338 (kersting1@llnl.gov).

Patents and Awards

In this section, we list recent patents issued to and awards received by Laboratory employees. Our goal is to showcase the distinguished scientific and technical achievements of our employees as well as to indicate the scale and scope of the work done at the Laboratory.

Patents

Photoswitchable Method for the Ordered Attachment of Proteins to Surfaces

Julio A. Camarero, James J. DeYoreo, Youngeun Kwon
U.S. Patent 7,972,827 B2
July 5, 2011
With this method, proteins can be attached to any solid support while controlling the attachment orientation. The method is efficient, does not require a protein to be purified before it is attached, and can be activated by ultraviolet light. Spatially addressable arrays of multiple protein components can be generated using standard photolithographic techniques.

System Using Data Compression and Hashing Adapted for Use for Multimedia Encryption

Douglas R. Coffland
U.S. Patent 7,978,847 B1
July 12, 2011
Within this system for multimedia encryption, a data compression module receives and compresses a media signal into a compressed data stream. Then a data-acquisition module receives and selects a set of data from the compressed stream. A hashing module receives and hashes the set of data into a key word. The method includes the steps of compressing a media signal into a compressed data stream, selecting a set of data from the stream, and hashing the set of data into a key word.

Deionization and Desalination Using Electrostatic Ion Pumping

William I. Bourcier, Roger D. Aines, Jeffrey J. Haslam, Charlene M. Schaldach, Kevin C. O'Brien, Edward Cussler
U.S. Patent 7,981,268 B2
July 19, 2011
This method, apparatus, and system are used for purifying ionic solutions, such as desalinating water. Engineered charged surfaces sorb ions from the solutions. Surface charge is applied externally and synchronized with oscillatory fluid movements between parallel charged plates. Ions are held in place during fluid movement in one direction and then released for transport during movement in the opposite direction by removing the applied electric field. In this way, the ions, such as salt, are "ratched" across the charged surface from the feed side to the concentrate side. The process itself is simple and involves only pumps, charged surfaces, and manifolds for fluid collection.

Chemical Microreactor and Method Thereof

Jeffrey D. Morse, Alan Jankowski
U.S. Patent 7,993,534 B2
August 9, 2011
This method for creating a chemical microreactor includes forming at least one capillary microchannel in a substrate having at least one inlet and outlet. At least one heater is integrated into the chemical microreactor. The capillary microchannel is interfaced with a liquid chemical reservoir at the microchannel inlet. The microchannel is also interfaced with a porous membrane near its outlet. Another porous membrane is positioned beyond the outlet and is embedded with at least one catalyst material.

Passive Microfluidic Array Card and Reader

Lawrence Christopher Dugan, Matthew A. Coleman
U.S. Patent 7,993,583 B2
August 9, 2011
The microfluidic array card and reader system is used for analyzing samples. The microfluidic array card has a transport section, or sections, for moving the sample from the card's loading section to the array windows. The reader system includes a housing, a receiving section for the microfluidic array card, a viewing section, and a light source that directs light to the window of the microfluidic array card and to the viewing section.

MEMS-Based Fuel Cells with Integrated Catalytic Fuel Processor and Method Thereof

Alan F. Jankowski, Jeffrey D. Morse, Ravindra S. Upadhye, Mark A. Havstad
U.S. Patent 7,993,785 B2
August 9, 2011
This method is for incorporating catalytic materials into the fuel flow-field structures of microelectromechanical systems– (MEMS-) based fuel cells, which enable catalytic reforming of a hydrocarbon-based fuel, such as methane, methanol, or butane. Methods of fabrication are also disclosed.

Low Loss, High and Low Index Contrast Waveguides in Semiconductors

Tiziana Bond, Garrett Cole, Lynford Goddard, Jeff Kallman
U.S. Patent 7,995,892 B2
August 9, 2011
This system includes a waveguide structure comprising a core of an alloy of group III–V materials surrounded by an oxide (which may include one or more group III–V metals), wherein an interface of the oxide and core is characterized by oxidation of the alloy for defining the core. A method in one approach includes oxidizing a waveguide structure comprising an alloy of group III–V materials for forming a core of the alloy surrounded by an oxide.

Carbon Fuel Particles Used in Direct Carbon Conversion Fuel Cells

John F. Cooper, Nerine Cherepy
U.S. Patent 7,998,627 B2
August 16, 2011
This system is for preparing particulate carbon fuel for use in a fuel cell. Finely divided carbon particles are placed in the fuel cell along with a gas containing oxygen. The finely divided carbon particles are exposed to one of the following substances: carbonate salts; molten sodium-hydroxide; molten potassium hydroxide; molten lithium hydroxide; mixed hydroxides; or alkali and alkaline earth nitrates.

Awards

Lawrence Livermore has received honors for its efforts to move breakthrough ideas from the Laboratory into the marketplace. The Laboratory captured three awards from the **Federal Laboratory Consortium for Technology Transfer**. The three awards represent the most won this year by any institution among the more than 250 federal government laboratories and research centers that comprise the consortium. Microelectromechanical systems–based adaptive optics optical coherence tomography won an **Outstanding Technology Development Award**. This invention allows ophthalmologists to take a three-dimensional picture of the breadth and depth of the retina. **Catherine Elizondo**, a business executive in Livermore's Industrial Partnerships Office, was selected as the **Technology Transfer Professional of the Year**. Elizondo set a new Laboratory record for transferring seven technologies to companies in a single year. An **Outstanding Commercialization Success Award** was earned for glycophorin cell lines, which can be used to produce a special monoclonal antibody that might help researchers better understand cancer and heart disease.

Frank Wong of Livermore's Physical and Life Sciences Directorate and **Kristen Beahm** of the Domestic Nuclear Detection Office's (DNDO's) National Technical Nuclear Forensics Center (NTNFC) have been recognized for leading the development and coordination of the first-ever National Strategic Five-Year Plan for Improving the Nuclear Forensics and Attribution Capabilities of the U.S. Wong and Beahm received the **DNDO Director's Team Award** from the **Department of Homeland Security** in recognition of their accomplishment.

William Daitch, assistant director of DNDO and director of NTNFC, wrote: "The National Strategic Plan was the first of its kind, cutting across multiple departments and some major mission areas that had never been corralled into one high-level plan." Working closely with the White House National Security staff, Wong and Beahm led, facilitated, coordinated, and integrated the plan with the support of the departments of Defense, Energy, Homeland Security, State, and Justice, the Office of the Director of National Intelligence, and the Executive Office of the President.

Randy Pico, senior superintendent and safety officer of the Engineering Directorate, was selected by **DeVry University** from an alumni pool of more than 200,000 members as a **member** of ***The Pinnacle***, which focuses on the "unsung heroes and hidden gems" working for great companies, influencing tomorrow's leaders, and affecting policy in business and technology. Membership in *The Pinnacle* is designed to highlight the value of an education from DeVry and its Keller Graduate School of Management to prospective and current students, employers, licensing agencies, government officials, and the community at large.

Chad Noble, a weapons designer and engineer in the Weapons and Complex Integration Principal Directorate, has been named a winner of a **Defense Programs Employee of the Quarter Award** by the **National Nuclear Security Administration** (NNSA). Recipients of the award are recognized for going beyond the call of duty in supporting the mission of NNSA's Defense Programs. Noble was recognized for designing and analyzing a recent Lawrence Livermore hydrotest fired at Site 300's Contained Firing Facility, which improved understanding of a use-control technology present in the current U.S. nuclear weapons stockpile and under consideration for future life extension programs. Don Cook, NNSA's deputy administrator for Defense Programs, says, "The Defense Programs Employee of the Quarter Awards recognize the commitment to improving the way we do business by those who lead by example. NNSA is fortunate to have talented and dedicated professionals who are truly leaders in their fields working to promote our nuclear security mission."

Abstract

Weapons Diagnostics Technology Revolutionizes Cancer Treatment

In 2014, a revolutionary particle accelerator born out of the Laboratory's nuclear weapons program may begin to appear in hospitals to deliver lifesaving proton therapy to cancer patients who would otherwise receive traditional and often-dangerous radiation treatments. Because protons have a relatively large mass, they produce minimal lateral side scatter in the tissue. The proton beam is highly focused on the tumor and creates only low-dose side effects in surrounding tissue. The linear accelerator for the new device will be just 4 meters long, require very little shielding, and cost much less than today's systems, which are the size of a basketball arena. The design grew out of an accelerator developed to radiograph dense, nonnuclear test devices. A suggestion to accelerate protons instead of electrons led to a partnership that received funding from the University of California Davis Cancer Center to develop a proton-acceleration prototype. A commercialization agreement was later signed with TomoTherapy, Inc. Today, a TomoTherapy spinoff, Compact Particle Acceleration Corporation of Livermore, California, is developing further prototypes and, with assistance from Laboratory scientists, refining the device for clinical use.

Contact: George Caporaso (925) 422-7852 (caporaso1@llnl.gov).

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Coming Next Issue

The Energy Sector of Tomorrow

Livermore's high-performance computing capabilities and expertise in modeling promise to rapidly advance the nation's development of clean energy technologies.

Also in December

• Laboratory researchers are developing a sensitive technique to identify virus mutations that may jump from host to host.

• The Advanced Radiographic Capability will create an x-ray video of a target implosion during National Ignition Facility experiments, with recording rates up to 50 billion frames per second.

• Military planners use the Laboratory's Counterproliferation Analysis and Planning System to evaluate other nations' capabilities to manufacture weapons of mass destruction.

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